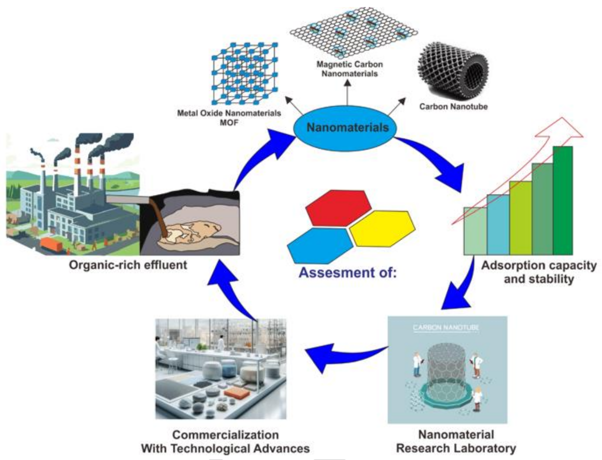
Global NEST Journal, Vol 28, No X, pp 1-24

A Review of Nanomaterials as Adsorbents for Organic-Rich Effluent Treatment and Its Life Cycle Assessment

Yudha Gusti Wibowo[1,2], Aris Setiawan[2,3], Dyah Ayu Larasati[2,4], Elli Prastyo[2,5], Zainal Mustakim[2,6], Dedy Anwar[2,7], Bimastyaji Surya Ramadan[8]* and Hana Safitri[1]

[1]Department of Mining Engineering, Faculty of Technology and Industry, Insitut Teknologi Sumatera, Lampung, Indonesia.
[2]Chemical Engineering Department, Faculty of Engineering, Universitas Gadjah Mada, Sleman, Yogyakarta, Indonesia.
[3]Department of Chemical Engineering, Faculty of Engineering, Universitas Lampung, Lampung, Indonesia.
[4]Departement of Agricultural Industrial Technology, Faculty of Technology and Industry, Insitut Teknologi Sumatera, Lampung, Indonesia.
[5]Department of Chemical Engineering, Institut Teknologi Petroleum Balongan, Indramayu, West Java, Indonesia.
[6]Departement of Chemical Engineering, Faculty of Engineering, Universitas Muhammadyah Gresik, East Java, Indonesia.
[7]Department of Bioprocess Engineering, Faculty of Biotechnology, Institut Teknologi Del, Toba, North Sumatera, Indonesia
[8]Department of Environmental Engineering, Universitas Diponegoro, Semarang, Indonesia
Received: 21/01/2025, Accepted: 17/04/2025, Available online: 09/02/2026
*to whom all correspondence should be addressed: e-mail: bimastyaji@live.undip.ac.id
https://doi.org/10.30955/gnj.07262

Graphical abstract



Abstract

The treatment of organic-rich effluents poses significant challenges in wastewater management due to the complex nature of contaminants and the limitations of conventional treatment methods. This review explores the potential of nanomaterials as advanced adsorbents for the remediation of organic pollutants, highlighting their unique physicochemical properties such as high surface area, tunable porosity, and reactivity. Carbon-based nanomaterials, including carbon nanotubes (CNTs) and graphene, along with metal-organic frameworks (MOFs) and layered double hydroxides (LDHs), demonstrate superior adsorption capacities and stability, making them suitable for diverse effluent compositions. However, despite their promising performance in laboratory settings, challenges such as high production costs, material stability, and scalability hinder their widespread industrial application. This review also identifies key future directions, including technological advancements, scaling up and commercialization strategies, and interdisciplinary research to bridge existing knowledge gaps. By addressing these challenges through innovative research and development, nanomaterials have the potential to significantly enhance the efficiency and sustainability of wastewater treatment processes, contributing to global environmental remediation efforts.

Keywords: Nanomaterials, Organic-rich effluent, Adsorption, Wastewater treatment, Environmental remediation.

1. Introduction

The effective treatment of organic-rich effluents poses a critical challenge in modern wastewater management. These effluents, often generated by industries such as rubber processing, aquaculture, paper manufacturing, and food production, contain high concentrations of organic compounds that can lead to severe environmental pollution if not properly treated [1–4]. Effluents are typically characterized by high levels of chemical oxygen demand (COD), nitrogen, phosphorus, and other organic loads, rendering them unsuitable for direct discharge into water bodies [5]. Traditional methods like anaerobic digestion face significant limitations when addressing these high organic load effluents, highlighting the need for advanced, more efficient technologies that can not only improve treatment efficiency but also reduce operational costs [6].

Yudha Gusti Wibowo, Aris Setiawan, Dyah Ayu Larasati, Elli Prastyo, Zainal Mustakim, Dedy Anwar, Bimastyaji Surya Ramadan and Hana Safitri. (2026), A Review of Nanomaterials as Adsorbents for Organic-Rich Effluent Treatment and Its Life Cycle Assessment, *Global NEST Journal*, **28**(XX), 1-24.

Current advancements in wastewater treatment involve various technologies aimed at removing organic and inorganic contaminants. Techniques such as microbial fuel cells, biosorption, electrocoagulation, and advanced oxidation processes have been employed to enhance the treatment of organic-rich effluents (Deng & Zhao, 2015; Z. Liu *et al.*, 2019; Santos *et al.*, 2015; Verma *et al.*, 2022). However, ensuring stable effluent quality and meeting stringent discharge standards remains a significant challenge, particularly in complex systems like wastewater stabilization ponds, which often require additional treatment steps (Khalfbadam *et al.*, 2017). Furthermore, high nitrogen levels in untreated effluents contribute to eutrophication, emphasizing the need for advanced biological nitrogen removal processes (Wedyan *et al.*, 2016). Emerging concerns such as the presence of microplastics in wastewater sludge further complicate the management of organic-rich waste streams, necessitating new approaches (Koutnik *et al.*, 2021).

Nanomaterials have recently emerged as a groundbreaking solution for addressing these challenges in effluent treatment. Their unique physicochemical properties, such as high surface area, reactivity, and adsorption capacity, make them particularly effective in contaminant removal (Carpenter *et al.*, 2015; Ding *et al.*, 2021; Ramadan *et al.*, 2024; Rameshkumar *et al.*, 2019). The integration of functionalized nanomaterials, including zeolite and activated carbon, has significantly enhanced the anti-fouling properties of treatment systems, offering promising advancements over traditional methods (Rameshkumar *et al.*, 2019). However, despite their demonstrated laboratory-scale success, the broader environmental and health implications of nanomaterial deployment are not well understood. Existing literature has largely focused on performance metrics, while overlooking the sustainability aspects throughout the material's lifecycle—from raw material sourcing to disposal. **This gap highlights the need for a comprehensive LCA of nanomaterials as adsorbents in wastewater treatment**, particularly for organic-rich effluents, to fully evaluate their environmental viability and guide responsible scaling and implementation.

The novelty of this study lies in its focus on the LCA of nanomaterials used as adsorbents in organic-rich effluent treatment, an area that remains underexplored. This research will be the first to present a holistic analysis of the environmental impacts of nanomaterials throughout their production, application, and disposal stages in wastewater treatment. This study will cover essential aspects such as the characterization of organic-rich effluents, adsorption mechanisms, environmental and health impacts, reusability, and future research directions. By evaluating the LCA of nanomaterials, this study aims to optimize their use for more sustainable wastewater treatment solutions, providing critical insights into their long-term viability and challenges in real-world applications.

2. Recent Trends in Published Papers

Figure 1 provides a comprehensive overview of the scientific publications related to a specific research field, categorized into journal contributions, publication trends over time, article types, and subject areas. The method for get this result following the previous studies (Gusti Wibowo *et al.*, 2024; Wibowo *et al.*, 2025). In terms of journal contributions, *Chemosphere* emerges as the leading journal, followed by *Chemical Engineering Journal*, *Journal of Environmental Chemical Engineering*, and *Science of the Total Environment*. This distribution highlights the interdisciplinary nature of the field, with significant contributions from journals focusing on environmental science, chemical engineering, and applied sciences. These findings underscore the relevance of this research area to both academic and industrial advancements.

The publication trends over time show a remarkable growth in the number of documents, particularly after 2015. This exponential increase reflects the rising importance of the field in addressing global challenges. The sharp rise in publications post-2020 may be attributed to intensified research activities driven by funding opportunities, policy changes, or urgent environmental and industrial demands. This trend underscores the field's expanding impact and the growing recognition of its significance across scientific communities.

The analysis of article types reveals that research articles form the majority of publications, emphasizing the experimental and exploratory focus of the field. Review articles are also prominent, indicating the necessity of synthesizing existing knowledge to guide future research directions. Other article types, such as book chapters, conference abstracts, and short communications, contribute to a smaller extent, suggesting that the primary emphasis remains on detailed, original research contributions. This distribution reflects a balance between generating new insights and consolidating existing knowledge.

The subject areas involved in the research highlight the dominance of environmental science and chemical engineering, which are closely aligned with the application-driven nature of the field. Materials science, chemistry, and energy also play significant roles, demonstrating the importance of developing new materials and processes. Biochemistry, genetics, and molecular biology show a growing integration of biological systems, while engineering reflects practical applications. Fields like agricultural sciences and earth sciences make smaller contributions, pointing to niche applications or interdisciplinary overlaps that could be further explored.

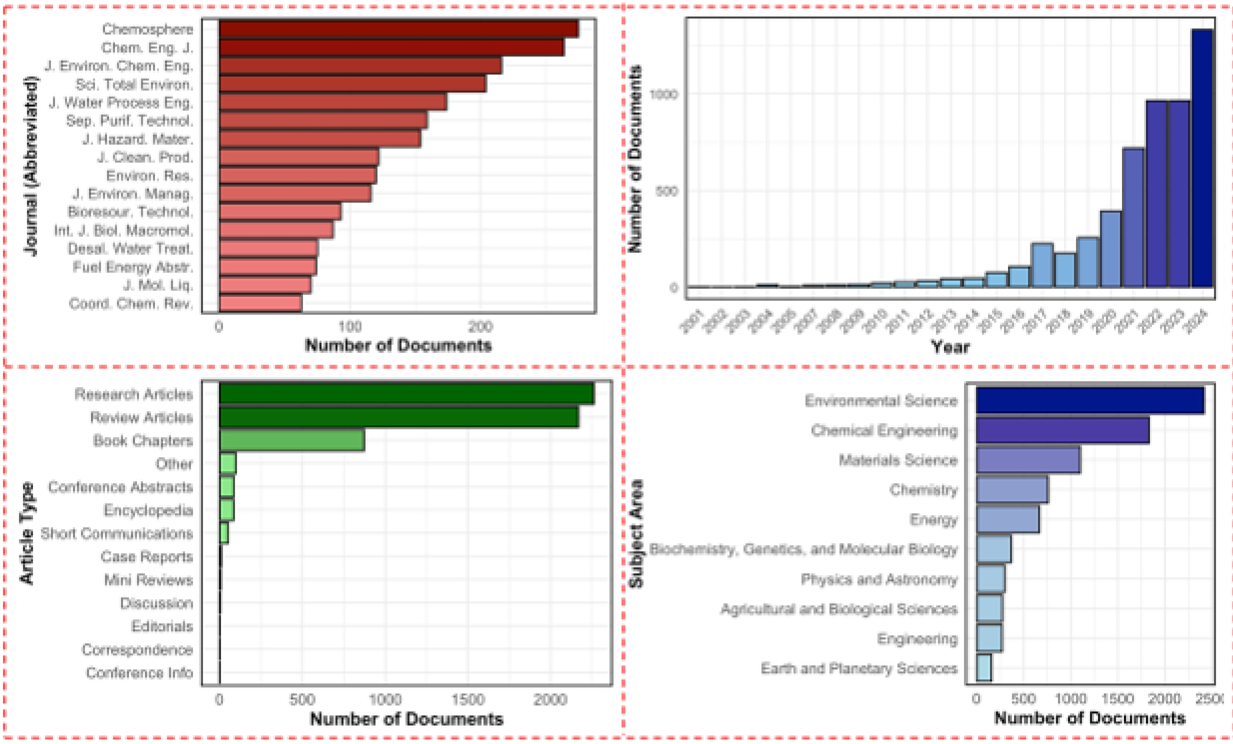


Figure 1. Trends in published papers according to Scopus database.

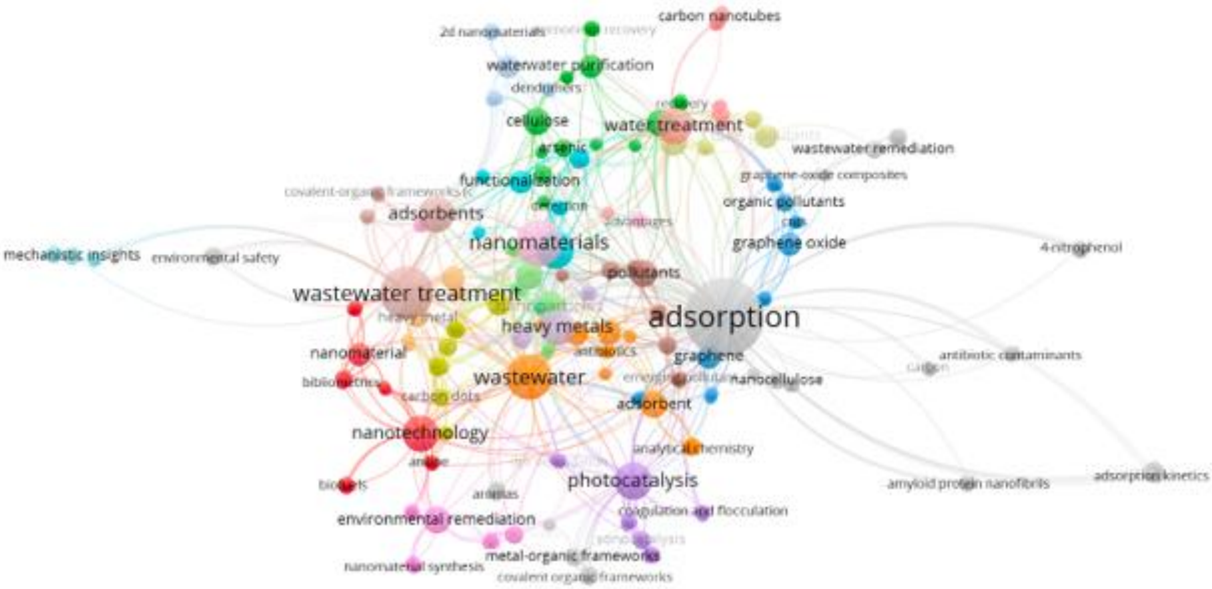


Figure 2. Mapping of keyword

Figure 2 highlights the network structure of keywords and their interconnections within a body of research data. This network map is based on citation and co-occurrence relationships, and it offers insights into the main research themes, areas of focus, and emerging trends in the field. At the center of the network, the keyword adsorption appears prominently, indicating its central role and significant occurrence in the research dataset. It is closely linked to terms like wastewater treatment, nanomaterials, adsorbents, heavy metals, and functionalization, which collectively suggest a focus on the development and application of adsorption-based techniques for environmental remediation, particularly in the treatment of wastewater and the removal of pollutants such as heavy metals. Clusters in the network represent thematic areas within the research. For instance, nanotechnology and photocatalysisform distinct clusters, highlighting their importance as complementary or alternative approaches to adsorption in water purification and pollutant removal. Keywords such as graphene oxide, metal-organic frameworks, and cellulose reflect the use of advanced materials, including bio-based and synthetic materials, to enhance adsorption efficiency and selectivity. The map also reveals connections to keywords like environmental remediation, water purification, and antibiotics, which indicate the broader applicability of these technologies beyond heavy metals, extending to organic pollutants and emerging contaminants. Keywords like functionalization and mechanistic insights suggest ongoing efforts to improve material performance through chemical or structural modifications and a focus on understanding the underlying processes. Peripheral terms such as coagulation and flocculation and 4-nitrophenol imply specific areas of application or comparisons to other water treatment techniques. Meanwhile, terms like bibliometrics and nanomaterial synthesissuggest that the field is actively growing, with attention being paid to both the development of new materials and the bibliographic analysis of research trends.

3. Characteristics and Types of Nanomaterials

Nanomaterials are integral to the development of advanced adsorbents for treating organic-rich effluents, owing to their unique physicochemical properties such as high surface area, tunable porosity, and strong adsorption capabilities. These properties make them highly effective in removing a wide range of pollutants from wastewater, and their versatility allows them to be applied in various environmental remediation efforts. **Figure 3** showed the several materials classified as nanomaterials.

Carbon-based nanomaterials, including carbon nanotubes (CNTs) and graphene, are particularly notable for their exceptional mechanical, optical, and electrochemical properties. These characteristics enhance their adsorption performance through interactions such as hydrophobic forces, van der Waals forces, and π-π bonding (Z. Yu *et al.*, 2020). CNTs and reduced graphene oxide (rGO) have been extensively utilized for removing organic pollutants and have broader applications in environmental remediation (Fan, 2024; T. Liu *et al.*, 2022). Their high specific surface area and porous structures significantly enhance their ability to capture contaminants, including heavy metals, organic compounds, and dyes, from aqueous solutions (Diel *et al.*, 2022; W. Yu *et al.*, 2022).

The versatility of carbon-based nanomaterials extends to their integration into hybrid nanocomposites. For instance, graphene-based materials combined with halloysite nanotubes (HNTs) and ZnO have demonstrated enhanced photocatalytic degradation and adsorption of organic dyes, illustrating the synergistic effects of these nanomaterials in complex water treatment scenarios (Dissanayake *et al.*, 2023a; Park *et al.*, 2023). Magnetic carbonaceous nanomaterials are also noteworthy due to their ease of retrieval and reuse, making them sustainable options for repeated applications in wastewater treatment (Saleem & Zaidi, 2020; Shen, 2023).

Among the various types of nanomaterials used in adsorption, multi-walled carbon nanotubes (MWCNTs) have shown significant promise. Their layered configuration and molecular capture capabilities enable the effective retention of contaminants, making them suitable for treating a diverse range of pollutants (W. Yu *et al.*, 2022). Similarly, graphene oxide (GO) has been widely used for adsorbing various contaminants, including dyes like methylene blue, due to its high surface area and functional groups that facilitate strong electrostatic interactions with pollutants (Dissanayake *et al.*, 2023b).

Metal and metal oxide nanoparticles also play a pivotal role in developing advanced adsorbents, thanks to their high surface area, catalytic properties, and versatility. These nanoparticles are highly effective in removing dyes, antibiotics, heavy metals, and other organic compounds from wastewater (Anele *et al.*, 2022). For example, zinc oxide (ZnO), titanium dioxide (TiO_2), and cerium dioxide (CeO_2) are valued for their photocatalytic properties, which enable them to harness solar energy for activating photocatalytic reactions that degrade persistent pollutants (Fatimah *et al.*, 2021). The integration of ZnO and CeO_2 nanoparticles in processes such as U/ZnO and O_3/ZnO has proven effective in eliminating pharmaceuticals like trimethoprim from water (Taie *et al.*, 2021).

The combination of metal and metal oxide nanoparticles in nanocomposites has also been effective in specific adsorption applications. For instance, magnetic nanoparticles and transition metal sulfides can be easily separated from treated water using external magnetic fields, making them sustainable for repeated use in effluent treatment (Izadi *et al.*, 2023). Additionally, the dual role of metal oxide nanoparticles as adsorbents and photocatalysts significantly enhances water treatment processes by providing efficient removal of contaminants and reducing the need for chemical reagents (I. M. F. Cardoso *et al.*, 2021).

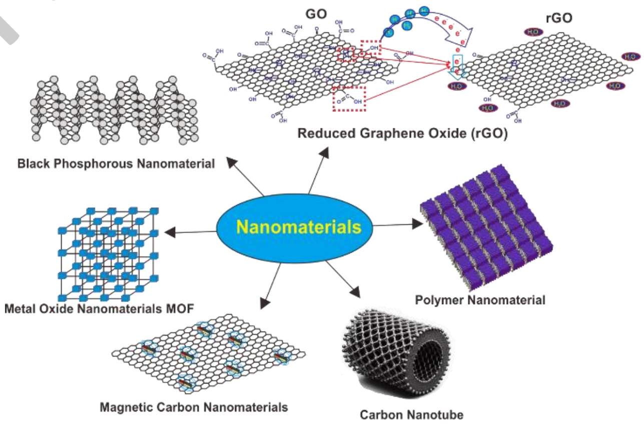


Figure 3. Types of Nanomaterials

Polymeric and composite nanomaterials have garnered considerable interest due to their unique properties, which combine the versatility of polymers with the functionality of nanoparticles. Polymeric nanomaterials are highly effective in various environmental applications, particularly wastewater treatment. For example, polymeric nanofibers have been successfully used to extract uranium from seawater, demonstrating their versatility and effectiveness in specific adsorption processes (G. Zhang, 2024). Additionally, polymeric nanomaterials have been explored for catalytic applications, such as synthesizing water-soluble gold nanoparticles through polymerized mesoionic N-heterocyclic carbene-gold(I) complexes (Nguyễn *et al.*, 2021).

Composite nanomaterials, especially those incorporating two-dimensional nanomaterials like graphene, graphene oxide, and molybdenum disulfide, have shown significant potential in enhancing the performance of polymeric coatings. These materials have been utilized to develop anticorrosive coatings effective in protecting surfaces from environmental degradation (Huang *et al.*, 2020). Moreover, polymeric nanomaterials based on polyaniline have demonstrated high performance in anion-exchange-driven adsorption processes, such as capturing $Cr_2O_7^{2-}$, highlighting their efficiency in selective adsorption applications (Pan, 2024).

The incorporation of inorganic and carbon nanomaterials into polymeric membranes has also been instrumental in addressing biofouling challenges in water treatment applications. For example, anti-biofouling polymeric membranes developed through surface modification with nanomaterials have shown enhanced performance, further emphasizing the versatility of composite nanomaterials in environmental applications (N. Zikalala *et al.*, 2023). Additionally, polymeric nanocomposites like polyacrylamide/gelatin–iron lanthanum oxide nanohybrids have been developed for removing antibiotic drugs and other contaminants from wastewater, showcasing their efficiency and sustainability in adsorption processes (Parveen, 2023).

The physicochemical properties of nanomaterials are fundamental to their effectiveness as adsorbents in treating organic-rich effluents. Properties such as surface area, porosity, surface chemistry, chemical stability, and reactivity significantly influence their adsorption capacity and efficiency in removing pollutants from wastewater. Understanding and manipulating these properties are crucial for developing advanced materials tailored for specific environmental remediation applications.

For example, carbon-based nanomaterials like CNTs and graphene exhibit high electrical conductivity, thermal stability, and mechanical strength. Their high specific surface area enhances their ability to interact with organic pollutants through various mechanisms, including van der Waals forces, π-π bonding, and hydrogen bonding (Giannakoudakis *et al.*, 2022). This makes them highly versatile and efficient adsorbents in water treatment technologies. Similarly, metal and metal oxide nanoparticles, such as GO and ZnO, possess high surface areas and light absorptivity, enabling them to effectively engage with a diverse range of pollutants and thereby enhancing their efficiency in water treatment processes (Tene *et al.*, 2022).

Surface area, porosity, and functionalization are critical physicochemical attributes that determine the performance of nanomaterials in adsorption applications. High surface area provides more active sites for contaminant interactions, thus enhancing adsorption processes. For instance, metal-organic frameworks (MOFs) are known for their high porosity and surface area, making them highly effective in adsorbing a wide range of contaminants from wastewater (Taheri & Tsuzuki, 2021).

Porous materials like MOFs and covalent organic frameworks (COFs), with their high pore volume and interconnected structures, provide ample space for the diffusion and trapping of pollutants. The tunable pore size distribution in these materials allows for the selective adsorption of specific contaminants, enhancing the overall efficiency of water treatment processes (Elmehrath *et al.*, 2023; L. Feng *et al.*, 2020). High porosity is particularly beneficial in applications requiring the removal of large molecules or high concentrations of pollutants, as it facilitates the movement and capture of contaminants within the adsorbent structure.

Functionalization, which involves modifying the surface of nanomaterials with specific chemical groups, is essential for enhancing their selectivity and adsorption efficiency. Functionalized nanomaterials are designed to interact more effectively with target pollutants through mechanisms such as electrostatic interactions, hydrogen bonding, or π-π interactions. For example, surface-functionalized electrospun polymer microfibrous membranes with magnetic iron oxide nanoparticles demonstrate enhanced magnetoactive properties, making them highly effective in adsorbing contaminants like ofloxacin from aqueous media (Papaphilippou *et al.*, 2022).

The combination of high surface area, tailored porosity, and strategic functionalization results in nanomaterials that are highly effective in treating organic-rich effluents. For example, porous carbon materials derived from MOFs possess a unique combination of high specific surface area, tailorable porosity, and easy functionalization, making them versatile and efficient adsorbents for wastewater treatment (Yao *et al.*, 2020). These materials can efficiently capture a wide range of pollutants, including heavy metals and organic compounds, from contaminated water sources (Guerrero-Fajardo *et al.*, 2020).

Chemical stability and reactivity are also critical properties that significantly affect the performance of nanomaterials in adsorbent applications. These properties determine the durability, efficiency, and overall effectiveness of nanomaterials in various environmental remediation processes, including adsorption, catalysis, and photocatalysis. Nanomaterials with high surface areas and electron-rich characteristics often exhibit excellent chemical stability and thermal resistance. These features enhance their reactivity, making them highly efficient in applications requiring rapid electron transfer kinetics and robust surface renewal, such as environmental remediation and energy production (A. R. Cardoso *et al.*, 2021). For instance, CNTs are known for their large specific surface area and reactivity, which make them effective adsorbents for removing heavy metal ions and other contaminants from wastewater (F. Khan *et al.*, 2021).

Metal-organic frameworks (MOFs) are another class of nanomaterials noted for their exceptional chemical stability and reactivity. These materials maintain their structural integrity under various environmental conditions, ensuring long-term effectiveness in removing contaminants from water (Maciel *et al.*, 2023). The reactivity of MOFs can be tailored through functionalization, enhancing their adsorption capabilities and selectivity for specific pollutants, making them highly effective in treating organic-rich effluents (Rasmi *et al.*, 2021).

Graphitic carbon nitride heterostructure nanocomposites also show significant potential due to their multifunctional properties, including enhanced reactivity towards organic pollutants. The synergistic effects of the components within these nanocomposites lead to improved photocatalytic performance, which is critical for degrading organic contaminants in water treatment applications (Glažar *et al.*, 2023). The chemical stability of these nanocomposites ensures their durability and effectiveness in challenging environmental conditions, making them suitable for sustainable water treatment technologies.

Polymer-based devices and remediation strategies further highlight the importance of chemical stability and reactivity in environmental applications. These materials are designed to efficiently remove emerging contaminants from water, leveraging their high chemical stability and reactivity to provide sustainable solutions for wastewater treatment (Alipoori *et al.*, 2021). Additionally, black phosphorus nanomaterials exhibit strong adsorption capabilities and exceptional stability in aqueous environments. Their reactivity plays a pivotal role in their adsorption capacity and overall efficiency in treating organic-rich effluents, underscoring their potential as promising materials for advanced water treatment technologies (Hawash *et al.*, 2022).

Synthesis and functionalization techniques are crucial for developing nanomaterials with tailored properties that enhance their performance in environmental applications. These methods significantly improve the adsorption capacity, selectivity, and overall effectiveness of nanomaterials in removing various pollutants from wastewater. Controlling the size, structure, and morphology of nanomaterials during synthesis is essential for optimizing their effectiveness in adsorption processes.

The sol-gel method, for instance, is widely used to produce metal oxide nanomaterials due to its versatility and ability to yield materials with highly controlled composition and structure (Huston *et al.*, 2021; Luca *et al.*, 2021). Hydrothermal synthesis is another prominent method known for its simplicity, controllability, and effectiveness in growing well-defined nanomaterials under high-temperature and high-pressure conditions (Tawade *et al.*, 2021; Abu-Nada *et al.*, 2020). Both methods are often integrated with techniques like microwave-assisted synthesis to improve efficiency and eco-friendliness (Maarouf *et al.*, 2022). Functionalization techniques, such as grafting and co-condensation, further refine the surface properties of nanomaterials to enhance their reactivity and selectivity for specific contaminants (Bukowski *et al.*, 2021; Gómez *et al.*, 2021).

Overall, the characteristics and types of nanomaterials, including carbon-based, metal and metal oxide, and polymeric composites, offer a comprehensive toolkit for addressing the multifaceted challenges of wastewater treatment. Their unique properties and capabilities enable efficient adsorption and degradation of various pollutants, making them indispensable in modern environmental remediation efforts. Continued research and development in these areas will further enhance their applicability and effectiveness in creating sustainable water treatment solutions.

4. Adsorption Mechanisms and Efficiencies

4.1. Adsorption Mechanisms

Adsorption mechanisms are fundamental to understanding how nanomaterial-based adsorbents remove contaminants from organic-rich effluents. The process primarily involves chemical interactions between the functional groups on the adsorbent surface and the adsorbate molecules, leading to the formation of metal-organic complexes or cation exchange reactions, driven by the adsorbent's high cation exchange capacity. These interactions occur through various mass-transport mechanisms, such as bulk transport within the liquid phase, diffusion through the fluid film surrounding the adsorbent particles, and penetration into the micropores and macropores of the adsorbent (Özacar *et al.*, 2008). The effectiveness of the adsorption process is influenced by the surface area, physicochemical properties, and the availability of surface sites to interact with adsorbate molecules. **Figure 4** showed the illustration of adsorption mechanism of pollutants onto surface areas and pores adsorbent.

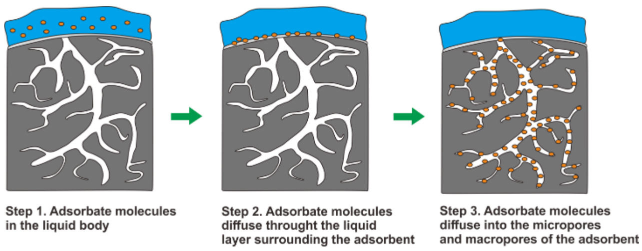


Figure 4. Adsorption mechanisms

Two primary mechanisms—physisorption and chemisorption—govern the adsorption processes of nanomaterials. Physisorption, or physical adsorption, involves weak interactions between the adsorbate molecules and the surface of the adsorbent, such as van der Waals forces, hydrogen bonding, and electrostatic interactions. This non-specific and reversible mechanism allows the adsorption of a wide range of organic molecules without altering their chemical structure. Physisorption is characterized by relatively low adsorption energies, typically ranging from 4 to 40 kJ/mol, indicating the involvement of weak forces (Wen, 2023; Nejatbakhsh *et al.*, 2022). Due to its reversible nature, physisorption is advantageous in applications requiring the regeneration of adsorbents, as it enables efficient adsorption-desorption cycles.

Physisorption is especially effective when adsorbate molecules are physically attracted to the adsorbent's surface without forming chemical bonds. This mechanism is crucial in processes where the rapid capture and release of adsorbates are required, such as in the removal of biomolecules like proteins and enzymes from wastewater. These interactions are driven by electrostatic forces and van der Waals interactions, making physisorption suitable for applications in biotechnological and environmental fields (Rahmani & Lyubartsev, 2023).

In contrast, chemisorption involves the formation of strong chemical bonds between the adsorbate and the adsorbent surface, characterized by higher adsorption energies, typically ranging from 80 to 400 kJ/mol (Nxumalo, 2023; Sudibyo *et al.*, 2022). This mechanism is generally irreversible, as the adsorbate forms a stable chemical bond with the adsorbent, altering the chemical structure of the adsorbate. Chemisorption is highly specific and selective, making it ideal for applications that require strong and stable adsorption, such as the removal of heavy metals or organic pollutants from wastewater. Factors such as temperature, pH, and the nature of the adsorbent material significantly influence chemisorption efficiency. For instance, increasing temperature can provide the necessary activation energy for bond formation, enhancing the adsorption process (Omodolor *et al.*, 2020).

Balancing physisorption and chemisorption is crucial for optimizing adsorption efficiency. A combined mechanism ensures both rapid uptake and stable retention of contaminants. For example, in the adsorption of heavy metal ions like Pb(II) and Cu(II) using nanomaterials, a mix of these mechanisms allows for the effective capture and stable retention of these ions (Fan, 2024). The adsorption energy and interaction nature can be fine-tuned by modifying the surface chemistry of adsorbents, enabling precise control over adsorption processes to meet specific environmental and industrial requirements (Kaur *et al.*, 2022).

The surface properties of nanomaterials, including surface area, porosity, surface functionalization, and surface charge, are critical in determining their effectiveness as adsorbents. A high specific surface area and well-developed porosity provide more active sites for adsorbate molecules, increasing the likelihood of adsorption. For example, nanomaterials like MXenes, with their large specific surface area and tunable interlayer spacing, are excellent for adsorbing various contaminants through synergistic adsorption-photocatalysis processes (Gopalram *et al.*, 2023). Similarly, activated carbon modified with inorganic or carbon nanomaterials exhibits enhanced adsorption capacity due to increased surface area and optimized porosity, making it highly effective in water treatment applications (Y. Zhang *et al.*, 2022).

Surface functionalization significantly impacts adsorption efficiency by enhancing specific interactions with target contaminants through mechanisms such as hydrogen bonding, π-π stacking, or electrostatic interactions. For instance, functionalized graphene derivatives and dendrimers show increased adsorption efficiency for removing heavy metal ions and organic pollutants from wastewater (Abid *et al.*, 2023; Ojembarrena *et al.*, 2022). These modifications can also improve the selectivity of the adsorption process, making the nanomaterial more effective for specific pollutants.

The surface charge of nanomaterials plays a crucial role in adsorption mechanisms, particularly in physisorption and chemisorption. Nanomaterials with a negative surface charge can effectively attract and adsorb positively charged pollutants through electrostatic interactions. For example, nanomaterials with superior hydrophilicity and negatively charged potentials demonstrate enhanced adsorption capabilities for organic dyes and pollutants in water treatment applications (Z. Yu *et al.*, 2020). Additionally, the presence of reactive sites and the chemical stability of the material's surface are essential for chemisorption, where the formation of chemical bonds is necessary for efficient pollutant removal (Yin *et al.*, 2023).

Despite the advantages of surface properties, practical applications of nanomaterials face challenges such as aggregation, loss of specific surface area, and operational difficulties due to the high surface energy of nanoparticles. These issues can negatively impact adsorption efficiency, highlighting the need to address and optimize surface properties to maintain effective adsorption processes (Yao *et al.*, 2020). Surfactants and polymer binders are often used to stabilize nanomaterials and prevent aggregation, preserving their surface properties and ensuring consistent performance in practical applications (C. Zhang *et al.*, 2021).

In environmental remediation, optimizing the surface properties of nanomaterials is crucial for improving pollutant removal efficiency. For example, nanomaterials with tailored surface properties, such as halloysite-TiO_2 composites, show high efficiency in removing heavy metal ions due to their specific surface area, reactivity, and mechanical strength (G. Li *et al.*, 2020). Surface-engineered nanomaterials are increasingly utilized in advanced water treatment technologies, contributing to more effective and sustainable environmental solutions (Al-Hetlani *et al.*, 2021).

4.2. Factors Affecting Adsorption Efficiency

The efficiency of adsorption processes in nanomaterials, especially for treating organic-rich effluents, is influenced by several critical factors that must be carefully considered to optimize pollutant removal. These factors include the intrinsic properties of the nanomaterials, the characteristics of the pollutants, and the specific environmental conditions under which adsorption occurs. The surface properties of nanomaterials, such as surface area, porosity, functional groups, and surface charge, are fundamental in determining their adsorption efficiency. High surface area and well-developed porosity provide a greater number of active sites for adsorbate molecules, thereby enhancing overall adsorption capacity (Dao *et al.*, 2022). For instance, materials with tailored surface chemistry can offer specific binding sites that increase selectivity and efficiency in targeting particular contaminants (Saravanan *et al.*, 2022). The presence of functional groups on the surface can significantly impact the strength and nature of interactions between the adsorbent and the adsorbate, further influencing adsorption efficiency.

The type and concentration of pollutants in the effluent are also crucial factors affecting the adsorption efficiency of nanomaterial-based adsorbents. Complex water matrices containing various ions and organic compounds can alter the adsorption capacity and selectivity of nanomaterials. High concentrations of competing ions, for example, can hinder the adsorption of target pollutants, reducing overall efficiency (Feijoo *et al.*, 2023). Understanding these interactions is essential for optimizing adsorption processes and ensuring effective contaminant removal (Zaman *et al.*, 2021). Nanomaterials with functionalized surfaces are particularly effective in complex matrices, as they can be engineered to selectively adsorb specific contaminants, even in the presence of other competing species.

The physical characteristics of nanomaterials, including morphology, size, and composition, play a significant role in their adsorption efficiency. Nanomaterials with large specific surface areas and unique structural features, such as nano-sized particles and hierarchical pore structures, exhibit enhanced adsorption performance due to the increased availability of active sites (Tesfahunegn *et al.*, 2023). Designing and synthesizing nanomaterials with optimized properties, such as tailored pore sizes and specific surface functionalities, is crucial for improving their efficiency in adsorbing pollutants from organic-rich effluents.

Operational conditions, such as pH, temperature, and ionic strength, significantly influence adsorption efficiency. The pH of the effluent can directly affect the surface charge of nanomaterial adsorbents and the ionization state of the pollutants, thereby impacting adsorption capacity (Wadi *et al.*, 2021). At different pH levels, the competition between H^+ ions and other cations for binding sites on the adsorbent surface changes, influencing the overall adsorption performance. In acidic conditions, for example, the high concentration of H^+ ions may compete with positively charged contaminants for adsorption sites, potentially reducing cation adsorption efficiency. Conversely, in alkaline conditions, the deprotonation of surface functional groups can enhance the adsorption of anionic pollutants (Silva *et al.*, 2021). Understanding and optimizing the pH-dependent behavior of nanomaterials is essential for maximizing their performance in removing specific organic pollutants from wastewater.

Temperature is another key factor that affects the kinetics and thermodynamics of the adsorption process. Higher temperatures typically increase the kinetic energy of adsorbate molecules, leading to faster adsorption rates by enhancing molecule mobility and the reactivity of the nanomaterial surface. This temperature increase can also shift the adsorption equilibrium, often resulting in a higher equilibrium capacity for the adsorbent (Song *et al.*, 2023). However, elevated temperatures may also impact the structural stability of some nanomaterials, potentially decreasing adsorption efficiency. Careful control and optimization of temperature are necessary to ensure that the adsorption process remains effective and that the nanomaterials maintain their performance across a range of operating conditions (Barhoum *et al.*, 2021).

The ionic strength of the solution, determined by the concentration of ions present, significantly influences the electrostatic interactions between nanomaterials and contaminants. High ionic strength can lead to increased competition for adsorption sites, as more ions are present in the solution, potentially reducing the adsorption capacity and selectivity of the adsorbent (Njuguna, 2024). Additionally, ionic strength can affect the thickness of the electrical double layer surrounding the nanomaterials, influencing the overall adsorption mechanism. In high ionic strength solutions, compression of the electrical double layer can reduce repulsion between similarly charged particles, facilitating closer interaction between the adsorbent and the adsorbate. Understanding the role of ionic strength in adsorption processes is essential for designing nanomaterial-based adsorbents that function efficiently under various environmental conditions (Pirvu *et al.*, 2023).

Surface modification and the introduction of functional groups are crucial strategies for enhancing the adsorption efficiency of nanomaterials. Modifying the surface properties of nanomaterials, such as adding oxygen, nitrogen, or sulfur functional groups, can increase the number of active sites and improve interactions with target contaminants (Vieira *et al.*, 2022). These modifications often result in enhanced reactivity and selectivity, enabling the removal of specific pollutants more effectively. For example, hydroxyl-functionalized MXene Ti_3C_2Tx has shown significant improvements in the removal of radioactive cesium from nuclear wastewater, demonstrating the impact of targeted surface modifications on adsorption efficiency (Ariyanti *et al.*, 2023). Similarly, functionalizing cellulose with amidoxime groups enhances uranium adsorption from aqueous solutions, optimizing the adsorption mechanisms for more efficient pollutant removal (W. Liu *et al.*, 2022).

Combining surface modification techniques with the introduction of functional groups can lead to advanced materials with tailored surface chemistries. This approach is particularly effective for addressing specific environmental challenges, such as the removal of hazardous metal ions, organic dyes, and other persistent pollutants from water sources (Melnychuk *et al.*, 2021). Surface modification, including bio-inspired approaches like dopamine conjugation, not only enhances the biocompatibility of nanoparticles but also introduces functional amino groups that can be further modified to improve pollutant removal efficiency (Volov *et al.*, 2022). Optimizing the interplay between pH, temperature, ionic strength, and surface properties is essential for developing robust adsorption processes effective across different operational environments (Awad *et al.*, 2021).

Table 1. Application of nanomaterials in removing pollutans

Materials	Contaminant	Removal time and efficiency	Mechanism of Removal	References
BC-NZVI	Cr (IV) in soil	The immobilization efficiency of Cr(VI) and total Cr reached 100% and 92.9%, respectively, when 8 g/kg BC-NZVI was applied for 15 d	Electrostatic interaction	(Su *et al.*, 2016)
NZVI-HCS	Pb(II), Cu(II), and Zn(II) in water	The maximum adsorption capacities were 195.1, 161.9, and 109,7 mg/g or Pb(II), Cu(II), and Zn(II), Respectively	Electrostatic interaction and chemisorption	(Yang *et al.*, 2018)
MWCNTs	Zn(II)in water	The maximum adsorption efficiency was 96.27% at pH 5 for 6 h	Electrostatic interaction and surface complexation	(Moosa *et al.*, 2016)
TiO_2-NCH	Cd(II) and Cu(II) in water	The maximum adsorption efficiency of Cu(II) and Cd(II) from wastewater samples were 88.01% and 70.67%, respectively	Physical and chemical complexation	(Mohammad *et al.*, 2017)
Mesoporous carbonated TiO_2 NPs	Sr(II) in water	The maximum adsorption capacity of Sr(II) 204.4 mg/g at natural pH	Surface adsorpsion and chelation	(Mironyuk *et al.*, 2019)
$CoFe_2O_4$-CNTs	Bisphenol A	The BPA removal efficiency of 99% was obtained at a pH of 3 and maximum adsorption capacity 101.7 mg/g	π–π and Ionic interaction; hydrophopic interaction	(Al-Musawi *et al.*, 2022)
Fe_3O_4- (MWCNTs)	Methylene blue in water	The methylene blue removal efficiency of 96-97% was obtained at pH 8,3 and maximum adsorption capacity of 48.2 mg/g	Electrostatic interaction and chemisorption	(Abutaleb *et al.*, 2023)
CNTs-C@Fe-chitosan composite	Tetracycline	The Tetracycline removal efficiency of 96,1% was obtained and maximum adsorption capacity of 845.9 mg/g	Electrostatic interaction and π–π Stacking	(Álvarez-Torrellas *et al.*, 2016)
Polyethylenimine/MMT NC	Cr(IV) in water	The maximum adsorption capacity of Cr(VI) was achieved as 62.89 mg/g and removal efficiency 96.7%.	Electrostatic interaction	(Fayazi & Ghanbarian, 2020)
Alg/GO-HMDA	Pb(II)/Cu(II)/Cd(II) in water	The removal efficiency for Pb(II) is 100%; 98,18% for Cu; and 95,19% for Cd(II)	Chemisorption, Electrostatic interaction	(Majdoub *et al.*, 2021)
PAM-g-GRA	Pb(II)	The maximum adsorption capacity of PAM-g-graphene is 819.67 mg/g at pH 6		(Xu *et al.*, 2014)

Nanomaterials have demonstrated exceptional potential as adsorbents for organic and inorganic pollutants. **Table 1.** summarizes the performance of key nanomaterials such as carbon nanotubes (CNTs), graphene oxide (GO), and metal oxide composites in removing specific contaminants (e.g., heavy metals, dyes, and pharmaceuticals). The data highlights the interplay between material properties (e.g., surface functionalization), adsorption mechanisms (physisorption/chemisorption), and operational conditions (pH, contact time). For instance, MWCNTs achieved 96.27% Zn(II) removal at pH 5 (Moosa *et al.*, 2016), while functionalized graphene exhibited a Pb(II) adsorption capacity of 819.67 mg/g (Xu *et al.*, 2014). These examples underscore the superiority of nanomaterials over conventional adsorbents, setting the stage for the comparative analysis in Section 3.3.

4.3. Comparative Adsorption Studies

Comparative adsorption studies are essential for evaluating the performance of various adsorbents under controlled conditions, especially in the treatment of organic-rich effluents. These investigations provide critical insights into the adsorption capacities, kinetics, mechanisms, and selectivity of different nanomaterials, allowing for the optimization of materials and processes tailored to specific environmental challenges.

One study investigated the stepwise separation of calcium from an ammonium sulfate leaching system, where unburned carbon was removed effectively using iron-loaded tributyl phosphate (TBP) in a sulfate suspension. The synergistic interaction between adsorbent and target impurities resulted in enhanced separation efficiency, illustrating the importance of material-pollutant interaction specificity (W. Li *et al.*, 2023). Similarly, carbon nano-onions were shown to effectively adsorb pharmaceutical compounds such as antibiotics from wastewater, with adsorption efficiency influenced by variables such as pH and adsorbent dosage, reinforcing their sustainability and low-cost potential in water treatment (Kumari, 2023).

Hybrid nanofillers, such as reduced graphene oxide (r-GO) combined with montmorillonite (MMT), have also been studied for their dual functionality in enhancing the structural and flame-retardant properties of polymer composites (Kavimani *et al.*, 2021). Although not applied directly in wastewater treatment, these studies provide a useful analogy regarding the synergistic improvement of adsorbent performance through hybridization.

In terms of adsorption modeling, a comparative analysis involving bisphenol-A and diethyl phthalate on activated carbon demonstrated the value of both competitive and non-competitive models in deciphering adsorbate-adsorbent interactions, supporting the advancement of predictive modeling in multicomponent systems (Maruyama & Seki, 2021).

Quantitative data from various studies further highlight the superior performance of nanomaterial-based adsorbents compared to conventional materials. For instance, multi-walled carbon nanotubes (MWCNTs) demonstrated a maximum Zn(II) adsorption efficiency of 96.27% within 6 hours at pH 5 through electrostatic and surface complexation mechanisms (Moosa *et al.*, 2016). Similarly, $CoFe_2O_4$–CNT composites achieved a 99% removal efficiency of bisphenol A at pH 3, with an adsorption capacity of 101.7 mg/g, indicating strong π–π and ionic interactions (Al-Musawi *et al.*, 2022). In general, the mechanism of adsorption of heavy metals using carbon nanotubes is shown in the **Figure 5**.

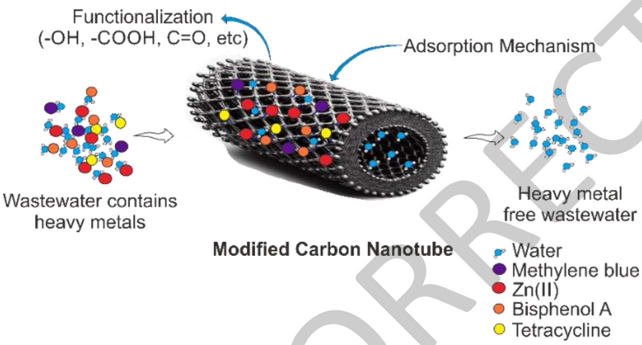


Figure 5. Mechanism adsorption of heavy metals using Carbon Nanotube

In terms of capacity, the CNTs-C@Fe-chitosan composite displayed exceptional performance with a maximum tetracycline adsorption capacity of 845.9 mg/g, showcasing the benefit of combining electrostatic interactions with π–π stacking (Álvarez-Torrellas *et al.*, 2016). Comparable efficiency was observed in PAM-g-graphene, which reached a Pb(II) adsorption capacity of 819.67 mg/g at pH 6, surpassing most conventional adsorbents (Xu *et al.*, 2014).

Metal oxide and composite nanomaterials have also demonstrated competitive performance. For example, mesoporous carbonated TiO_2 nanoparticles exhibited a Sr(II) adsorption capacity of 204.4 mg/g, while TiO_2-NCH composites removed 88.01% of Cu(II) and 70.67% of Cd(II) through physical and chemical complexation ((Mohammad *et al.*, 2017; Mironyuk *et al.*, 2019). Meanwhile, NZVI-HCS achieved capacities of 195.1, 161.9, and 109.7 mg/g for Pb(II), Cu(II), and Zn(II), respectively, utilizing a combination of electrostatic interaction and chemisorption (Yang *et al.*, 2018).

When compared to traditional activated carbon, nanomaterials clearly outperform in multiple categories. A comparative study on the removal of Auramine-O and Brilliant Green dyes showed that nanomaterial-based adsorbents had sorption capacities ranging from 257 to 544 mg/g and 247 to 395 mg/g, respectively—substantially higher than conventional microporous carbons (Ejsmont, 2024; Vieira *et al.*, 2022).

Additional comparative insights can be drawn from the performance of **mesoporous silica nanoparticles (MSNPs)**, which offer not only high surface area and thermal stability but also enhanced selectivity and ease of modification, making them highly competitive in dye removal applications (Alswieleh, 2023). Moreover, studies on **zwitterionic polymer brushes coated with MSNPs** further underscore the material's adaptability in achieving superior adsorption through tailored surface chemistry and functionalization (Alswieleh, 2023).

Finally, porous organic polymers enriched with heteroatoms have proven effective in capturing iodine vapor, demonstrating rapid kinetics, excellent moisture tolerance, and high reusability—traits that are transferable to aqueous phase contaminant removal (Das, 2023). These attributes collectively illustrate the expanding utility of nanomaterials across diverse environmental remediation contexts.

Comparative adsorption studies offer a critical foundation for selecting and designing adsorbents with optimal performance. Quantitative evidence strongly supports the superior efficacy of nanomaterial-based systems, especially in terms of adsorption capacity, removal efficiency, and reusability. As nanotechnology continues to evolve, these materials present a promising pathway toward sustainable and high-performance wastewater treatment solutions.

5. Environmental Impact and Life Cycle Assessment

5.1. LCA Methodologies

LCA is a comprehensive and systematic methodology used to evaluate the environmental impacts associated with a product or process throughout its entire life cycle, from raw material extraction to production, use, and final disposal. It provides a structured framework for analyzing environmental impacts, resource utilization, and potential trade-offs, enabling stakeholders to make informed decisions that promote sustainability across various industries. By considering the full spectrum of a product's life cycle, LCA helps identify opportunities to reduce negative environmental effects and enhance resource efficiency.

LCA methodologies are based on standardized frameworks established by the International Organization for Standardization (ISO), particularly ISO 14040 and ISO 14044. **Figure 6** Shows illustrates the general methodological framework for LCA. These standards outline the principles and framework for conducting LCA, including key stages such as goal and scope definition, inventory analysis, impact assessment, and interpretation of results (Guinée *et al.*, 2011; Shen *et al.*, 2022). The ISO standards ensure consistency, transparency, and comparability across different LCA studies, enhancing their reliability and credibility.

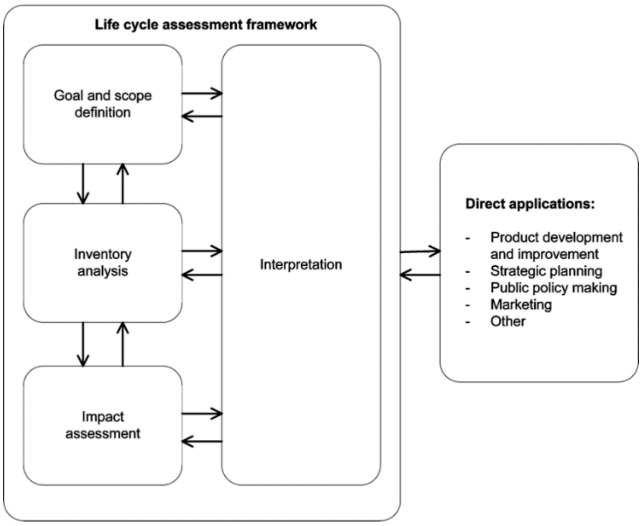


Figure 6. The general methodological framework for LCA (Guinée *et al.*, 2011)

LCA can be categorized into three main types: environmental LCA (E-LCA), social LCA (S-LCA), and economic LCA (E-LCA). Environmental LCA focuses on the environmental impacts of a product or process, such as greenhouse gas emissions and resource depletion. Social LCA assesses the social implications of production and consumption processes, including labor conditions and community impacts (Huertas-Valdivia *et al.*, 2020; Rahmah *et al.*, 2023). Economic LCA evaluates the cost-effectiveness and economic sustainability of a product. Integrating these three types into a unified framework, known as Life Cycle Sustainability Assessment (LCSA), allows for a more holistic evaluation of sustainability by considering environmental, social, and economic impacts together (Hannouf *et al.*, 2021).

The ISO standards emphasize the importance of clearly defining system boundaries, functional units, and relevant impact categories for each assessment. Proper documentation and transparent reporting are crucial for ensuring the reproducibility and credibility of LCA studies (Guinée *et al.*, 2011; Shen *et al.*, 2022). In addition to the ISO standards, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) have developed the UNEP/SETAC Life Cycle Initiative, which provides guidelines and frameworks tailored to various sectors, such as construction, agriculture, and manufacturing (Hellweg & Milà I Canals, 2014). These guidelines facilitate the application of LCA methodologies by providing sector-specific recommendations that enhance the adaptability of LCA across different industries.

Recent advancements in LCA frameworks include the integration of Building Information Modeling (BIM) in the construction sector. BIM enhances data collection and analysis, allowing for a more comprehensive assessment of building life cycles. This integration helps incorporate environmental considerations into the design and construction phases, although challenges remain in terms of data completeness and accuracy, particularly in covering all life cycle stages (H. Feng *et al.*, 2023; Soust-Verdaguer *et al.*, 2017). Additionally, the development of specific databases, such as Ökobau.dat, supports the application of LCA in construction by providing access to relevant environmental data (Gantner *et al.*, 2018).

Key impact categories considered in LCA.

LCA evaluates a broad range of impact categories that reflect the environmental consequences of a product's life cycle. These impact categories are essential for understanding the full spectrum of environmental impacts and for identifying potential areas for improvement.

- **Global Warming Potential (GWP):** GWP is one of the most critical impact categories in LCA. It assesses the contribution of greenhouse gas emissions to climate change, typically expressed in terms of carbon dioxide equivalents (CO_2e). This category is particularly relevant for industries with significant carbon footprints, such as energy production and transportation (Baral *et al.*, 2016; Geß *et al.*, 2020).
- **Eutrophication Potential:** This category evaluates the potential for nutrient runoff to cause excessive growth of algae in water bodies. Eutrophication can lead to oxygen depletion in aquatic ecosystems, harming aquatic life and disrupting natural processes (Kounina *et al.*, 2013). Eutrophication potential is especially relevant in agriculture, where nutrient management is a critical concern.
- **Acidification Potential:** Acidification potential measures the potential for emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to contribute to acid rain. Acid rain can have severe effects on ecosystems, including soil degradation and the loss of biodiversity, as well as damage to infrastructure (Geß *et al.*, 2020).
- **Resource Depletion:** This category assesses the consumption of natural resources, such as fossil fuels, minerals, and water, throughout the life cycle of a product. Resource depletion is a key concern for industries that rely heavily on non-renewable resources, as it directly impacts long-term sustainability (Grzesik, 2018; Rugani & Benetto, 2012).

In addition to these environmental impact categories, S-LCA incorporates social indicators to evaluate the social implications of production processes. These indicators include labor conditions, community impacts, and human rights considerations (Huertas-Valdivia *et al.*, 2020; Rahmah *et al.*, 2023). By integrating these diverse impact categories, LCA frameworks provide a more nuanced understanding of sustainability and support more informed decision-making across various sectors.

As LCA methodologies continue to evolve, their integration with emerging technologies and frameworks will enhance their applicability and effectiveness in promoting sustainable practices. As industries strive to reduce their environmental and social footprints, LCA remains a vital tool for evaluating the sustainability of products and processes, ensuring that efforts toward sustainability are grounded in comprehensive and scientifically sound assessments.

5.2. Environmental Impacts of Nanomaterial Synthesis

The synthesis and application of nanomaterials have revolutionized numerous industries due to their unique properties and diverse benefits. However, the environmental impacts associated with their production, especially concerning energy consumption and emissions, have raised critical concerns. Understanding these impacts is essential for developing more sustainable production processes and mitigating environmental risks.

Nanomaterial synthesis is inherently energy-intensive, often requiring high temperatures and pressures that lead to substantial energy consumption and significant greenhouse gas (GHG) emissions. The lifecycle of carbonaceous nanomaterials, for instance, includes multiple stages—manufacturing, processing, and disposal—all of which contribute to environmental burdens (Myojo & Ono-Ogasawara, 2018). Furthermore, the production of nanomaterials can generate hazardous waste and emissions, posing risks not only to the environment but also to human health (Beaudrie *et al.*, 2013; Mrowiec, 2016).

LCA have emerged as critical tools for evaluating the environmental performance of nanomaterials across their entire lifecycle. These assessments help identify the trade-offs between the technological benefits of nanomaterials and their environmental costs, providing insights that can guide the development of more sustainable practices (Hischier, 2014; Pallas *et al.*, 2020). For example, while nanosilver's antimicrobial properties make it valuable for use in textiles, its synthesis and disposal can lead to environmental pollution and toxicity issues (Walser *et al.*, 2011). This highlights the need for a balanced approach to assessing the environmental impacts of nanomaterial synthesis.

One of the most significant environmental concerns associated with nanomaterial synthesis is the substantial energy required for production. The energy-intensive nature of these processes often results in a high carbon footprint. For example, the synthesis of hollow silica nanospheres is known for its considerable energy consumption and the associated CO_2 emissions, emphasizing the need for more energy-efficient production methods (Gao *et al.*, 2013; Pallas *et al.*, 2018). Additionally, the extraction of raw materials for nanomaterial production can lead to the depletion of natural resources. This process not only contributes to resource scarcity but also to the degradation of ecosystems from which these materials are sourced (Mrowiec, 2016).

As the demand for nanomaterials continues to grow, there is increasing pressure on natural resources, making it crucial to consider alternative, more sustainable sources. The integration of green chemistry principles into nanomaterial synthesis represents a promising approach to reducing energy and resource consumption. Researchers are increasingly focusing on optimizing synthesis routes and utilizing renewable resources to minimize the environmental impact of nanomaterial production (Dhingra *et al.*, 2010; Gulumian *et al.*, 2023). Strategies such as developing low-energy synthesis methods and using biodegradable materials are being explored to reduce the overall environmental footprint of nanomaterial production.

The synthesis of nanomaterials is also associated with the emission of greenhouse gases (GHGs) and other pollutants. Production processes can release harmful substances, including volatile organic compounds (VOCs) and particulate matter, both of which contribute to air pollution and climate change (Holder *et al.*, 2013; Pallas *et al.*, 2018). For instance, the incineration of nanomaterials can produce toxic byproducts such as dioxins, posing severe environmental and health risks (Holder *et al.*, 2013). Moreover, engineered nanomaterials (ENMs) can enter the environment through various pathways, including wastewater discharge and atmospheric release, leading to potential ecological impacts (Nowack *et al.*, 2013).

Once in the environment, ENMs can undergo transformations that may enhance their toxicity or bioavailability, increasing the risks they pose to ecosystems and human health. The bioaccumulation of these materials in living organisms is particularly concerning, as it could lead to long-term adverse effects on biodiversity and food safety (Rickerby *et al.*, 2015). Therefore, understanding the environmental fate of nanomaterials—including their persistence, transformation, and impact on ecosystems—is crucial for developing strategies to mitigate these risks.

While nanomaterials offer numerous technological advantages, their synthesis and application present significant environmental challenges. Addressing these challenges requires a comprehensive approach that includes assessments of energy consumption, resource use, and pollutant emissions. Life Cycle Assessments are invaluable for understanding and mitigating the environmental impacts associated with nanomaterial synthesis. As the field of nanotechnology evolves, developing greener synthesis methods and stricter regulatory frameworks will be essential to promoting sustainable use and ensuring that the benefits of nanomaterials do not come at the expense of the environment.

5.3. Comparative LCA of Nanomaterials and Conventional Adsorbents

The growing application of nanomaterials in environmental remediation has spurred comparative LCA studies to evaluate their environmental performance relative to conventional adsorbents such as activated carbon and zeolites. While nanomaterials like CNTs, graphene, and nanosilver exhibit superior adsorption efficiency, versatility, and chemical stability, these benefits are counterbalanced by significant environmental trade-offs that must be scrutinized through a comprehensive life cycle perspective.

Nanomaterials frequently outperform conventional adsorbents in terms of functional performance. For instance, CNTs can achieve similar or higher pollutant removal rates with lower material quantities, potentially reducing total material consumption and operational emissions (Arora & Attri, 2020). This efficiency, however, must be weighed against the energy- and resource-intensive processes required to synthesize such advanced materials. Case studies, such as the life cycle inventory of cadmium selenide (CdSe) quantum dots, illustrate how nanomaterial production often involves high energy demand and the use of hazardous reagents, raising concerns about upstream emissions and occupational exposure risks (Sengül & Theis, 2014).

Environmental benefits of nanomaterials can be observed in specific applications. For example, incorporating nanosilver into textiles has reduced reliance on chemical disinfectants, while maintaining antimicrobial efficacy, thereby lowering the overall environmental burden during use and maintenance (Pourzahedi & Eckelman, 2015; Walser *et al.*, 2011). Similarly, CNTs and graphene-based membranes are being developed for water purification systems that minimize chemical use and produce cleaner effluent. However, these materials may persist in aquatic environments post-use, posing ecotoxicological risks due to bioaccumulation and long-term transformation processes (Rickerby, 2013; P. Sharma *et al.*, 2022).

One of the core environmental trade-offs in nanomaterial use lies in their **production phase**, which is often associated with high electricity consumption, emissions of greenhouse gases, and generation of toxic byproducts. For example, the production of CNTs through chemical vapor deposition can result in a substantial carbon footprint that may offset their downstream benefits in adsorption performance (Wu *et al.*, 2019). Additionally, **release during use and disposal** stages remains largely unquantified. Engineered nanomaterials (ENMs) may be unintentionally released into ecosystems through wastewater, industrial discharge, or landfill leachates, where they interact dynamically with biota, often exhibiting behavior distinct from their bulk counterparts (Mitrano & Nowack, 2017).

The **lack of complete LCA datasets**, particularly for the use and end-of-life phases, continues to hamper comprehensive impact evaluations (Nizam *et al.*, 2021). Most LCAs disproportionately focus on synthesis, overlooking emissions during product use, degradation behavior, and post-consumer management. This gap is further complicated by the unique physicochemical transformations that nanomaterials undergo, including agglomeration, surface oxidation, or binding with organic matter, all of which can alter their fate and toxicity (Gavankar *et al.*, 2012; Sørensen *et al.*, 2019).

Recent assessments have advocated for the integration of **environmental risk assessment (ERA)** and **sustainability frameworks** alongside traditional LCAs. These tools enable risk–benefit evaluations, especially in the absence of long-term toxicity data (Romero-Franco *et al.*, 2017). For example, studies on quantum dot applications and nanosilver in medical textiles have demonstrated the importance of weighing technical efficiency against potential environmental burdens throughout the life cycle (Chatzipanagiotou *et al.*, 2025). Incorporating **socio-economic considerations**, such as resource accessibility, production costs, and occupational health, is also essential for a holistic sustainability appraisal, albeit methodologically challenging (Brignon, 2011; Vance *et al.*, 2015).

Despite these challenges, comparative LCAs remain critical for guiding material selection in sustainable water treatment technologies. A case in point is the use of **graphene oxide-based membranes** in place of polymeric membranes, which, although initially more energy-intensive to fabricate, demonstrate longer lifespan, higher fouling resistance, and reduced need for chemical regeneration—leading to a favorable long-term environmental balance (Looney *et al.*, 2018).

Moving forward, the **development of nano-specific LCA methodologies** and **standardized characterization protocols** is imperative. Such tools should account for the complex interactions of ENMs in environmental systems, integrate dynamic exposure scenarios, and reflect real-world use patterns. Interdisciplinary efforts that combine materials science, toxicology, and environmental engineering are required to refine impact assessments and inform regulatory decision-making.

In conclusion, while nanomaterials offer transformative potential for environmental remediation, their sustainable deployment must be evaluated through robust, holistic LCA frameworks. Recognizing and addressing the environmental trade-offs across the full material life cycle—including synthesis, use, and disposal—is essential for ensuring that the net benefits of nanotechnologies are not undermined by hidden ecological costs. Future research should prioritize comparative case studies, database development, and integration of LCA with risk and sustainability assessment tools to support responsible innovation in nanotechnology.

6. Regeneration and Reusability of Nanomaterials

The treatment of organic-rich effluents, particularly from industrial wastewater, increasingly relies on nanomaterials due to their unique adsorption properties and ability to target a broad range of organic pollutants. However, their widespread application is limited by challenges related to cost and sustainability. Regeneration techniques, which allow for the repeated use of nanomaterials, play a crucial role in reducing operational costs and enhancing sustainability in wastewater treatment processes. This section explores various regeneration methods, their impact on adsorption capacity and material integrity, and the effectiveness of nanomaterials in case studies demonstrating their reusability for organic-rich effluent treatment.

Nanomaterials used as adsorbents must be regenerated to restore their adsorption capacities after becoming saturated with pollutants. Common regeneration techniques include thermal, chemical, and electrochemical methods (**Figure 7**), each offering specific advantages and limitations based on the properties of the nanomaterial and the nature of the organic pollutants.

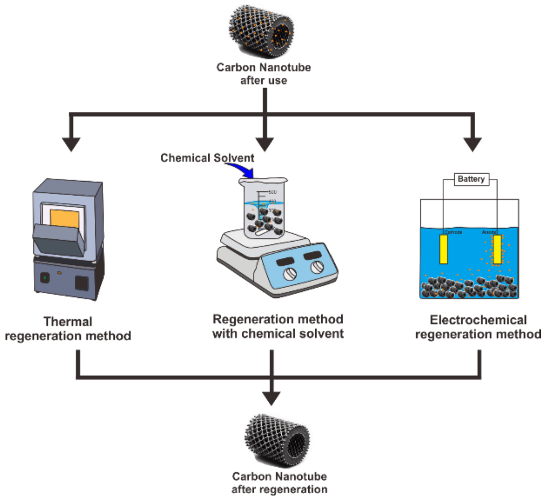


Figure 7. Nanomaterials regeneration method

Thermal regeneration, widely used for carbon-based adsorbents such as activated carbon and biochar, involves heating the materials to desorb trapped organic pollutants. While effective, thermal regeneration requires significant energy input, raising concerns about its efficiency and sustainability (Ren *et al.*, 2011). For example, while bimetallic mesoporous zeolites can be regenerated through heat treatment, the long regeneration times and high energy demands limit practical applications (Lee *et al.*, 2019). To mitigate these limitations, microwave-assisted thermal regeneration has been explored, demonstrating quicker desorption of pollutants and reduced energy costs. However, high energy consumption remains a challenge for large-scale applications (Zheng *et al.*, 2016).

Chemical regeneration utilizes solvents or chemical reagents to desorb pollutants from the surface of nanomaterials, often restoring adsorption capacities without causing significant structural degradation. This method is effective for adsorbents like carbon nanotubes (CNTs) and metal-organic frameworks (MOFs), where oxidizing agents and solvents can successfully desorb pollutants (Cansado *et al.*, 2023). However, the environmental impact of chemical solvents, including potential secondary pollution, remains a significant concern (Ren *et al.*, 2011). Greener alternatives, such as plasma treatments, are being investigated to reduce reliance on harmful chemicals and improve sustainability.

Electrochemical regeneration combines adsorption with electrochemical processes to restore the adsorptive capacity of nanomaterials. This technique, which involves applying an electric current to facilitate pollutant desorption, has been shown to regenerate sawdust-based adsorbents effectively while simultaneously degrading the adsorbed pollutants (Bouaziz *et al.*, 2017). Nanofibrous membranes, particularly effective in capturing organic dyes from industrial wastewater, have also demonstrated ease of regeneration through electrochemical processes (Y. Liu *et al.*, 2020). Despite its lower environmental footprint compared to thermal and chemical methods, the scalability of electrochemical regeneration for larger wastewater treatment systems remains an area of ongoing research.

The regeneration process can impact both the adsorption capacity and structural integrity of nanomaterials. While the goal is to restore adsorption efficiency, repeated regeneration cycles can degrade materials over time, potentially reducing their long-term viability. The ability of nanomaterials to maintain high adsorption capacities after multiple regeneration cycles is critical for their sustainable use. For example, biochar composites retained their adsorption efficiency after chemical regeneration, but the choice of regenerating agents was essential to prevent material degradation (Premarathna *et al.*, 2019). Metal-organic frameworks (MOFs) also maintained adsorption capacities across several cycles through chemical and electrochemical regeneration methods, though the effectiveness varied depending on the type of organic pollutants being treated (Imanipoor *et al.*, 2021).

In some cases, regeneration can even enhance the adsorptive properties of nanomaterials. Electrochemical regeneration has been shown to not only restore but also improve the adsorption capacity of sawdust-based materials, suggesting that, under the right conditions, regeneration could extend the functional lifespan of certain adsorbents beyond their original capacities (Bouaziz *et al.*, 2017). However, repeated regeneration cycles can also compromise structural integrity. For instance, graphite-based adsorbents showed reduced durability due to their nonporous nature after repeated electrochemical regeneration (Hussain *et al.*, 2015). High calcination temperatures during thermal regeneration have been reported to eliminate functional hydroxyl groups in iron-oxide-based adsorbents, leading to a decline in adsorption capacity in subsequent cycles (Mukhopadhyay *et al.*, 2017).

The economic viability of using nanomaterials in wastewater treatment is closely linked to their regeneration capabilities. High initial costs can be offset by effective regeneration, making nanomaterials more feasible for large-scale applications (N. E. Zikalala *et al.*, 2023). From an environmental perspective, regeneration reduces the need for continuous production of new adsorbents, thereby lowering the environmental impact of nanomaterial synthesis. However, chemical regeneration can introduce secondary pollution if not managed properly, whereas electrochemical regeneration offers a more sustainable option by requiring fewer chemical reagents and degrading pollutants during the regeneration process (Bouaziz *et al.*, 2017).

The regeneration and reusability of nanomaterials are pivotal in improving the sustainability and economic viability of wastewater treatment systems. Advances in hybrid nanocomposites and tailored regeneration strategies have the potential to further enhance the performance and longevity of these materials. Continued research is needed to optimize regeneration techniques and scale up these technologies for broader industrial application, ensuring that the benefits of nanomaterials are fully realized in sustainable wastewater treatment solutions.

7. Health and Safety Considerations

The use of nanomaterials as adsorbents for treating organic-rich effluents has gained significant attention due to their exceptional properties and ability to effectively remove contaminants. However, health and safety concerns associated with these materials are critical to ensuring their responsible use, given the potential risks they pose to human health and ecosystems. Addressing these issues requires a comprehensive understanding of the toxicity and ecotoxicity of nanomaterials, the current regulatory frameworks, and the strategies for mitigating risks.

Nanomaterials, while highly effective in wastewater treatment due to their high surface area and reactivity, can exhibit significant toxicity risks to humans and ecosystems (**Figure 8**). Their small size allows them to interact with biological systems in ways that larger particles cannot, potentially leading to adverse health and environmental effects (De Luis *et al.*, 2011). For instance, carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene oxide (GO), commonly used in effluent treatment, have been shown to induce oxidative stress, inflammation, and cellular damage in both aquatic organisms and humans (Abbo *et al.*, 2021; Saroa *et al.*, 2023). These materials can generate reactive oxygen species (ROS), which disrupt cellular processes, leading to apoptosis or necrosis (Gubala *et al.*, 2018).

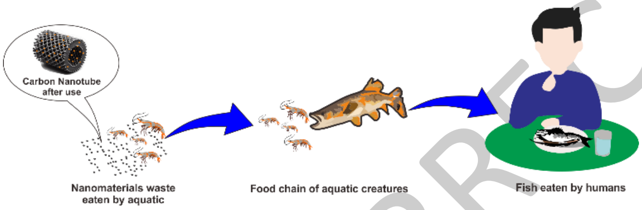


Figure 8. The process of nanomaterials waste accumulating in humans

The environmental implications of nanomaterials are further complicated by their potential to bioaccumulate. Nanoparticles can be absorbed by aquatic organisms, accumulate in their tissues, and biomagnify through food webs, posing long-term risks to both aquatic ecosystems and human populations (Aditya Kiran *et al.*, 2016; A. Sharma *et al.*, 2023). For example, CNTs have been found to accumulate in the tissues of aquatic organisms, potentially leading to ecological imbalances and health risks higher up the food chain (Sadare *et al.*, 2022). Studies have shown that even after treating wastewater, residual nanomaterials can persist and exhibit toxic effects on aquatic life, underscoring the need for thorough assessments of their environmental fate (Ashraf *et al.*, 2020).

Regulatory frameworks for managing the risks associated with nanomaterials in wastewater treatment are still evolving, with significant gaps that need to be addressed. Agencies such as the U.S. Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA) under the REACH regulation have implemented some guidelines, but these often fall short in addressing the unique properties and behaviors of nanomaterials (Krug & Nau, 2017; Lakhe *et al.*, 2019). The lack of standardized definitions and testing methods complicates regulatory compliance, and current regulations do not adequately consider the potential for bioaccumulation and long-term environmental effects of nanomaterials (Vidu *et al.*, 2020).

To mitigate the health and safety risks associated with nanomaterials, several strategies have been proposed. One effective approach is the adoption of green chemistry principles in the design and synthesis of nanomaterials. For instance, using plant extracts or other biogenic methods to synthesize nanoparticles reduces the reliance on hazardous chemicals, thereby lowering the potential for environmental contamination (M. Khan *et al.*, 2017). Surface modifications, such as PEGylation (the attachment of polyethylene glycol chains to nanoparticles), can also reduce the toxicity of nanomaterials by preventing protein adsorption and reducing cellular uptake (Walkey *et al.*, 2012).

Additionally, the development of biodegradable and non-toxic alternatives to traditional nanomaterials is gaining traction. Biopolymers like chitosan and nanocellulose, derived from lignocellulosic biomass, have shown promise as effective adsorbents in wastewater treatment (Sadare *et al.*, 2022; A. Sharma *et al.*, 2023). These materials are biodegradable and renewable, offering a more sustainable option compared to synthetic nanomaterials. Furthermore, integrating LCA into the development and application of nanomaterials can help identify opportunities to minimize environmental impacts and ensure their safe use in wastewater treatment (Feijoo *et al.*, 2019).

A comprehensive approach that includes safe design, green synthesis, lifecycle assessment, and robust regulatory frameworks is essential for mitigating the health and environmental risks associated with the use of nanomaterials in wastewater treatment. By implementing these strategies, the industry can harness the benefits of nanomaterials while ensuring safety and sustainability.

8. Future Directions and Challenges

The treatment of organic-rich effluents using nanomaterials has demonstrated considerable promise, driven by the superior physicochemical properties of these materials—such as high surface area, tunable porosity, and enhanced reactivity. Nonetheless, several key challenges must be addressed to transition nanomaterial-based solutions from laboratory research to large-scale, real-world applications. This section outlines a structured roadmap for future research, categorized into four critical domains (**Figure 9**).

One of the principal barriers to the widespread adoption of nanomaterials in wastewater treatment is their high production cost. Advanced synthesis techniques for materials such as CNTs, graphene, and MOFs often involve expensive precursors, high energy inputs, and complex processing steps. Future research must prioritize the development of low-cost and scalable synthesis methods, including the use of agricultural or industrial waste as precursor materials, green chemistry approaches, and energy-efficient production technologies. Innovations in catalytic regeneration and extended reuse cycles can also contribute to reducing long-term operational costs.

Figure 9. Key challenge of future research direction

Laboratory-scale synthesis often fails to translate efficiently to industrial-scale production. Challenges include batch inconsistency, morphological control, and maintaining material quality across larger volumes. Future work should focus on continuous-flow synthesis methods, process intensification techniques, and modular manufacturing systems. Integration with additive manufacturing (e.g., 3D printing of nanocomposite membranes) may also provide new avenues for scalable deployment. Importantly, pilot-scale studies are necessary to validate material performance in complex wastewater matrices and to inform techno-economic assessments for commercialization.

The absence of clear regulatory pathways and standardized characterization protocols remains a significant bottleneck. Most existing wastewater treatment regulations do not account for the unique properties and risks associated with engineered nanomaterials (ENMs). Collaborative efforts between researchers, industry stakeholders, and policy makers are needed to develop regulatory guidelines that cover the production, application, and disposal phases of nanomaterials. Harmonization of test methods for environmental fate, ecotoxicity, and material stability will support regulatory acceptance and facilitate technology transfer.

The potential toxicity and environmental persistence of nanomaterials pose risks that must be addressed to ensure their safe and sustainable use. Future research should focus on long-term ecotoxicological studies, bioaccumulation potential, and the development of nanomaterials with inherently lower toxicity profiles. Biodegradable and bio-based nanomaterials, such as chitosan or cellulose nanofibers, offer promising alternatives. Furthermore, LCA should be systematically integrated into material development workflows to identify and mitigate environmental impacts at every stage of the nanomaterial's life cycle.

9. Conclusion

The application of nanomaterials for the treatment of organic-rich effluents represents a promising advancement in wastewater management, addressing the limitations of conventional treatment methods. This review highlights the superior adsorption capacities, tunable properties, and potential for functionalization of nanomaterials, making them highly effective in removing a broad spectrum of contaminants. Carbon-based nanomaterials such as CNTs and graphene, along with MOFs and LDHs, have shown considerable potential to improve treatment efficiency and reduce environmental impacts.

Despite these advantages, the transition from laboratory-scale research to large-scale industrial applications remains challenging. The high cost and complexity of nanomaterial synthesis, coupled with issues related to stability and reusability in complex effluent matrices, present significant barriers to commercialization. Addressing these challenges will require continued innovation in cost-effective synthesis methods, robust material design, and the development of sustainable regeneration techniques to ensure long-term performance and economic feasibility.

Importantly, the practical integration of nanomaterials into existing wastewater treatment infrastructure is both feasible and necessary. Rather than replacing current systems, nanomaterials can be introduced as modular enhancements—such as in polishing units, membrane composites, or hybrid adsorptive-filtration systems—allowing utilities to incrementally upgrade performance without full-scale redesign. Their high efficiency at low concentrations supports compact system configurations, which are particularly beneficial for retrofitting in space-constrained facilities. Furthermore, nanocomposites and functionalized media can be engineered to complement conventional activated carbon, sand filters, or biological reactors, thus enabling synergistic removal of persistent pollutants.

Collaborative efforts among researchers, engineers, and industry stakeholders are needed to translate these materials from bench to plant, supported by pilot-scale demonstrations, robust LCA frameworks, and clear regulatory guidelines. In conclusion, by addressing the current limitations and strategically leveraging their unique properties, nanomaterials hold the potential to transform wastewater treatment systems into more resilient, efficient, and sustainable platforms for environmental protection.

10. CRedIT author statements

YGW: Conceptualization, visualization, writing the original manuscript; **DAL, EP, ZM, DA, BSR, HS**: Writing the original manuscript, review and editing. **AS**: Writing and visualization

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